

# Determinants of the Carotid Tortuosity Index: Evidence from Digital Subtraction Angiography

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## Abstract:

**Introduction:** Stroke remains one of the leading causes of death and disability worldwide, with ischemic stroke accounting for most cases. Structural vascular factors such as carotid artery tortuosity have gained attention as potential markers of vascular aging and cerebrovascular risk. The carotid tortuosity index (CTI), defined as the ratio of actual vessel length to the straight-line distance between two fixed points, provides a quantitative measure of arterial curvature. A CTI value of  $\geq 1.2$  indicates pathological tortuosity. Although noninvasive modalities such as CTA and MRA are frequently used, digital subtraction angiography (DSA) remains the gold standard for evaluating vessel geometry due to its higher spatial precision. This study aimed to determine the association of age, sex, and hypertension with CTI measured by DSA. **Methods:** A cross-sectional study was conducted from November to December 2025 at the Neurointervention Clinic, RS Pelni Jakarta, Indonesia, involving 61 adult patients who underwent carotid DSA. CTI was measured bilaterally using digital imaging software and classified as  $< 1.2$  (non-tortuous) or  $\geq 1.2$  (tortuous). Clinical data, including age, sex, and hypertension status, were collected from medical records and analyzed using bivariate tests. **Results:** Older age ( $\geq 65$  years), female sex, and hypertension were significantly associated with higher CTI values on both carotid sides. Tortuosity was more common among hypertensive patients and elderly females, indicating the influence of vascular remodeling and chronic hemodynamic stress. **Conclusion:** Carotid tortuosity increases with age, hypertension, and female sex. DSA-based CTI measurement provides a reliable and precise approach for evaluating vascular changes associated with cerebrovascular risk.

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**Keywords:** Carotid Tortuosity Index; Digital Subtraction Angiography; Hypertension; Aging; Gender Differences

## 1. Introduction

Stroke remains one of the leading causes of death and disability worldwide. According to the Global Burden of Disease and World Stroke Organization reports, the global incidence of stroke increased by approximately 70% between 1990 and 2021, with mortality rising by 44% during the same period. Ischemic stroke accounts for nearly two-thirds of all cases and contributes substantially to long-term functional impairment and reduced quality of life [1-4]. Understanding modifiable and structural vascular factors that predispose individuals to cerebrovascular disease therefore remains a major research

priority. Among these, carotid artery tortuosity has gained attention as a potential marker of vascular aging and cerebrovascular risk.

Carotid artery tortuosity refers to deviation from the normal linear course of the artery, presenting as elongation, kinking, or coiling [5]. Once considered a benign anatomical variant, carotid tortuosity has increasingly been recognized as a morphological change that can disturb cerebral hemodynamics, impair laminar flow, and promote endothelial dysfunction [6, 7]. These changes may predispose patients to ischemic events by altering shear stress or serving as loci for embolic stasis. Recent studies have reported an association between carotid tortuosity and ischemic stroke, particularly in the internal carotid artery, suggesting that tortuous morphology may contribute to cerebral hypoperfusion or atheroembolic phenomena [7, 8]. Quantifying such deviations objectively has led to the development of the Carotid Tortuosity Index (CTI), a standardized metric for assessing vascular curvature. The Carotid Tortuosity Index (CTI) provides a simple and widely used quantitative measure of arterial curvature, defined as the ratio of the actual vessel length to the straight-line distance between two fixed anatomical points. A CTI value of approximately 1.2 has been proposed as a practical upper limit of normal, distinguishing physiological curvature from pathological tortuosity [9].

Multiple biological factors contribute to vascular tortuosity. Zun *et al.* demonstrated, through Magnetic Resonance Angiography (MRA), that advancing age was positively correlated with vascular tortuosity and accompanied by reduced blood flow, while females exhibited higher geometric indices and more rapid age-related vascular alterations than males [10]. Although the same study found no significant association between hypertension and tortuosity [10], Pancera *et al.*, using echocolor Doppler imaging, reported a higher prevalence of hypertension among individuals with carotid kinking [11]. Similarly, Huang *et al.*, based on Computed Tomography Angiography (CTA), identified age and hypertension duration as independent risk factors for carotid tortuosity, whereas antihypertensive therapy appeared protective through its modulatory effects on vascular remodeling [12].

Although interest in carotid tortuosity has grown, digital subtraction angiography-based data remain limited, as most investigations rely on noninvasive modalities such as duplex ultrasound, CTA or MRA, which may fail to capture subtle vascular variations [13]. Digital subtraction angiography, however, remains the gold standard for vascular assessment because of its superior spatial resolution and dynamic visualization of vessel geometry [14]. A study by Jae Ho Kim *et al.* demonstrated measurable differences between MRA and DSA in evaluating vascular curvature, suggesting that DSA provides a more accurate and sensitive depiction of arterial morphology [15]. Its high precision allows accurate measurement of the vessel centerline and reliable calculation of the CTI. However, very limited studies have examined factors influencing CTI using DSA, particularly in the Indonesian population. Therefore, this study aimed to investigate the association of age, sex, and hypertension with the carotid tortuosity index measured by DSA.

## 2. Materials and Methods

This cross-sectional study was conducted from February to September 2025 at the Neurointervention Clinic, RS Pelni Jakarta, Indonesia. The study included adult patients aged 18 years and older who underwent digital subtraction angiography (DSA) of the carotid arteries for diagnostic purposes. Participants were recruited consecutively from the clinic during the study period.

### Study Participants

Patients scheduled for DSA were screened according to the inclusion and exclusion criteria. Those who met the criteria and agreed to participate underwent a structured medical interview and data collection, including demographic characteristics, clinical history, and DSA findings. Patients were excluded if they had a history of carotid endarterectomy or stent placement, severe atherosclerotic stenosis (>70%), connective tissue disorders such as Marfan syndrome or Ehlers–Danlos syndrome, or if they had poor-quality angiographic images that prevented accurate measurement. Participants who declined to provide consent were also excluded.

### Data Collection and Clinical Variables

Demographic and clinical data, including age, sex, and hypertension status, were collected from the patients' medical records. Hypertension was defined as a previously established diagnosis by a physician or ongoing use of antihypertensive medication. Age was recorded as a continuous variable and later categorized into two groups: below 65 years and 65 years or older [16].

### Assessment of CTI

All DSA procedures were performed using an Innova IGS 520 single plan imaging system (GE Healthcare, Chicago, IL, USA) by an experienced neurointerventional consultant. Vascular access was obtained via the femoral artery using a 5 French catheter with continuous heparinized saline infusion. Vascular access was obtained through the femoral artery using a 5 French catheter with continuous heparinized saline infusion. Standard anteroposterior projections were obtained, covering the carotid artery from its origin to the skull base. Both extracranial internal carotid arteries were assessed independently by an investigator blinded to clinical data. The proximal end of the eICA was defined at the carotid bifurcation and the distal end at the point where the artery entered the carotid canal. The curved distance between these two points was measured as the arc length, and the straight-line distance as the chord length.

The CTI was determined as the ratio between the actual curved vessel length and the straight-line distance of the same arterial segment, measured using digital imaging software. All measurements were performed by a single experienced neurointerventional consultant, blinded to clinical data, to minimize observer bias and inter-observer variability. According to Van Laarhoven *et al.* and Dilba *et al.*, a CTI value <1.2 was defined as normal (non-tortuous), whereas a CTI  $\geq 1.2$  was considered tortuous in the present study [9, 17].

### Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics for Windows, Version 27.0. Categorical variables were expressed as frequencies and percentages. The Chi-square test was applied to evaluate the association between CTI categories and independent variables such as age group, gender, and hypertension status. A p-value of less than 0.05 was considered statistically significant.

### Research Ethics

Ethical approval was obtained from the Ethics Committee of the Faculty of Medicine, Universitas Pelita Harapan (approval number: 287/K-LKJ/ETIK/X/2025). Written informed consent was obtained from all participants before enrollment.

## 3. Results

This study included a total of 61 participants who underwent carotid imaging assessment. The baseline demographic and clinical characteristics of the subjects are

summarized in Table 1. Most participants were younger than 65 years (65.6%), and the proportion of males and females was nearly equal (52.5% and 47.5%, respectively). Hypertension was present in 62.2% of the participants. The majority exhibited a CTI of less than 1.2 on both sides, with 73.8% on the right and 62.3% on the left.

**Table 1. Baseline Characteristics and CTI Profiles**

Subject characteristics	N (61 patients)
<b>Age</b>	
< 65 years	40 (65.6%)
≥ 65 years	21 (34.4%)
<b>Gender</b>	
Male	32 (52.5%)
Female	29 (47.5%)
<b>Right Carotid Tortuosity Index (CTI)</b>	
< 1.2	45 (73.8%)
≥ 1.2	16 (26.2%)
<b>Left Carotid Tortuosity Index (CTI)</b>	
< 1.2	38 (62.3%)
≥ 1.2	23 (37.7%)
<b>Hypertension</b>	
Yes	38 (62.2%)
No	23 (37.8%)

Bivariate analysis (Table 2) demonstrated significant associations between CTI and several clinical variables. Participants aged ≥ 65 years were more likely to exhibit CTI ≥ 1.2 on both the right (p = 0.032) and left sides (p = 0.001). Similarly, female subjects showed a higher prevalence of CTI ≥ 1.2 compared with males, with statistically significant differences on both sides (right p = 0.010; left p < 0.001). Hypertension was also significantly related to increased CTI values (right p = 0.017; left p = 0.001). These findings indicate that older age, female gender, and hypertension are associated with higher carotid tortuosity indices bilaterally.

**Table 2. Association Between Age, Gender, and Hypertension with Carotid Tortuosity Index (CTI) on the Right and Left Sides**

Variable		Carotid Tortuosity Index (CTI)					
		Right			Left		
		< 1.2	≥ 1.2	p value	< 1.2	≥ 1.2	p value
Age	< 65 years	33 (82.5%)	7 (17.5%)	<b>0.032*</b>	31 (77.5 %)	9 (22.5%)	<b>0.001*</b>
	≥ 65 years	12 (57.1%)	9(42.9 %)		7 (33.3%)	14 (66.7%)	
Gender	Male	28 (87.5%)	4 (12.5%)	<b>0.010*</b>	27 (84.4%)	5 (15.6%)	<b>0.000*</b>
	Female	17 (58.6%)	12 (41.4%)		11 (37.9%)	18 (62.1%)	
Hypertension	Yes	32 (84.2%)	6 (15.8%)	<b>0.017*</b>	30 (78.9%)	8 (21.1%)	<b>0.001*</b>
	No	13 (56.5%)	10 (43.5%)		8 (34.8%)	15 (65.2%)	

\*P value was considered significant if < 0.05

#### 4. Discussion

Carotid artery tortuosity, including elongation, kinking, and coiling, is an important vascular change that has been increasingly linked to the risk of ischemic stroke and intracranial aneurysm formation. Several studies have highlighted its clinical relevance. Liu *et al.* reported that internal carotid artery kinking contributes to ischemic stroke [18], while Aghasadeghi *et al.* further demonstrated that increased carotid and vertebral artery

tortuosity serves as an independent imaging predictor of acute ischemic events across both anterior and posterior circulations. [19] Saba et al. also demonstrated that the carotid tortuosity index was significantly associated with the presence of stroke [20]. In addition to its association with ischemic events, Laarhoven et al. reported that patients with ICA aneurysms exhibited significantly greater tortuosity, suggesting that abnormal vessel geometry may increase wall stress and contribute to aneurysm formation [9]. The potential mechanisms linking carotid tortuosity to ischemic stroke involve both hemodynamic and thrombotic pathways. Hemodynamically, excessive vessel curvature or kinking can narrow the lumen and disturb blood flow, leading to reduced cerebral perfusion. On the other hand, tortuosity may also induce endothelial injury at curved segments. Previous studies proposed that vortex flow patterns generated by tortuous vessels can cause endothelial dysfunction, platelet activation, and local thrombus formation [21-23].

Our study revealed a significant association between carotid tortuosity on both the right and left sides and several factors, including age, female sex, and hypertension, as assessed using DSA. Individuals aged 65 years and older showed a higher prevalence of  $CTI \geq 1.2$  on both sides, suggesting age-related increase in vascular tortuosity. Consistent with previous research, age showed a strong relationship with carotid tortuosity. Zhe Sun et al., using magnetic resonance angiography, reported that older individuals exhibited higher tortuosity indices accompanied by lower blood flow and velocity, suggesting an age-related decline in vascular elasticity [10]. Similarly, Kamenskiy et al., through cerebrovascular computed tomography angiography, observed progressive increases in carotid bulb diameter, bifurcation angle, and tortuosity of both the common and internal carotid arteries with each advancing decade of life [24]. Luigi Di Pino et al., using echocolor Doppler, further noted a bimodal pattern of carotid kinking and coiling, suggesting that congenital factors and age-related vascular remodeling both contribute to increased tortuosity in older adults [25]. With aging, the arterial wall gradually weakens due to elastin breakdown, collagen buildup, and endothelial changes, which together reduce its elasticity and ability to handle blood flow pressure. These degenerative changes cause the artery to stretch and bend, forming curves along its course. Repetitive pulsatile forces and long-standing hypertension further damage the vessel wall and make these curves more permanent. As a result, the combined effects of aging and continuous mechanical stress lead to increased carotid tortuosity in older adults [10, 26, 27].

Gender differences were also apparent in our study, with female participants exhibiting a higher prevalence of carotid tortuosity. This finding aligns with Martins et al., who reported that internal carotid artery anomalies such as kinking, coiling, and looping occur more frequently in women [28]. Although the MRA-based study by Zhe Sun et al. found no significant sex differences in bilateral ICAs, it suggested that age-related vascular changes were more pronounced in females [10]. These differences may be attributed to hormonal influences and structural factors, as postmenopausal estrogen decline reduces elastin-to-collagen ratios and increases vascular stiffness, thereby promoting arterial remodeling and greater tortuosity in women [28].

Our study also demonstrated a significant association between hypertension and increased carotid tortuosity, consistent with previous findings. Pancera et al., using echocolor Doppler, reported a higher prevalence of hypertension among individuals with carotid kinking, which was also linked to transient ischemic attacks [11]. Similarly, Gavrilenko et al., through CT angiography, identified hypertension, age over 60 years, and dyslipidemia as major risk factors for internal carotid artery tortuosity [29]. Laura Del Corso et al. further suggested that hypertension, along with aging and atherosclerosis, plays an important role in vascular morphological changes [30]. However, in contrast, Hai Fei Wang et al. found no significant relationship between tortuosity and vascular risk factors, including hypertension [31]. Hypertension may contribute to carotid tortuosity through several interrelated mechanisms. Chronic high blood pressure causes

degenerative changes in the arterial wall, leading to the loss of normal elasticity and adaptive motion of the vessel [11]. The sustained elevation of vascular resistance and sympathetic activity promotes smooth muscle cell proliferation and medial thickening, which further reduce wall compliance [12]. Over time, the increased intraluminal pressure and mechanical stress cause the arteries to elongate and dilate, resulting in stretching and deformation of the vascular wall. Additionally, hypertension-related aortic elongation and shifting of proximal branch points may alter the geometric configuration of the carotid arteries, predisposing them to kinking or coiling [11, 32].

The strength of this study lies in its use of DSA, the gold-standard imaging modality, to quantitatively evaluate carotid tortuosity through the CTI with high spatial accuracy and reliable measurement. Evidence from DSA-based evaluations remains limited, particularly in Southeast Asian populations, making these findings a valuable contribution to the regional literature. A standardized imaging protocol, blinded assessment, and single-observer analysis were applied to minimize bias and ensure data consistency. The significant associations observed between CTI, age, sex, and hypertension provide important insights into vascular remodeling and arterial aging. Clinically, these results support the potential role of CTI as a complementary imaging biomarker for early detection of cerebrovascular risk and for guiding preventive neurovascular management.

We acknowledge several limitations in this study. First, the cross-sectional design limits the ability to infer causality, and longitudinal studies are required to clarify the temporal relationship between risk factors and carotid tortuosity. Second, the duration and control of hypertension were not evaluated, making it unclear whether prolonged or uncontrolled hypertension contributes to greater tortuosity or if these changes are reversible with antihypertensive drugs. Third, because the study population consisted of patients undergoing DSA, many with previous cerebrovascular events, selection bias may have occurred. Fourth, other vascular risk factors such as obesity, dyslipidemia, and diabetes mellitus were not included in the analysis. Lastly, this single-center study with a relatively small sample size may limit the generalizability of the results.

## 5. Conclusions

The CTI serves as an important imaging parameter for detecting vascular structural changes that may predispose individuals to ischemic events through altered hemodynamics and thrombotic mechanisms. Our study demonstrated that increased CTI values were significantly associated with aging, female sex, and hypertension, supporting the role of vascular remodeling and decreased arterial elasticity in the development of carotid tortuosity. The observed associations suggest that carotid tortuosity may reflect underlying vascular remodeling and early arterial aging, serving as a potential imaging biomarker for cerebrovascular vulnerability. Incorporating CTI measurement into routine angiographic evaluation could therefore enhance early detection of individuals at risk for ischemic events and guide preventive strategies.

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